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Estimating the potential of rainfed agriculture in India: Prospects for water productivity improvements

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ABSTRACT

A detailed district and agro-ecoregional level study comprising the 604 districts of India was undertaken to (i) identify dominant rainfed districts for major rainfed crops, (ii) make a crop-specific assessment of the surplus runoff water available for water harvesting and the irrigable area, (iii) estimate the efficiency of regional rain water use and incremental production due to supplementary irrigation for different crops, and (iv) conduct a preliminary economic analysis of water harvesting/supplemental irrigation to realize the potential of rainfed agriculture. A climatic water balance analysis of 225 dominant rainfed districts provided information on the possible surplus runoff during the year and the cropping season. On a potential (excluding very arid and wet areas) rainfed cropped area of 28.5 million ha, a surplus rainfall of 114 billion m^3 (Bm^3) was available for harvesting. A part of this amount of water is adequate to provide one turn of supplementary irrigation of 100 mm depth to 20.65 Mha during drought years and 25.08 Mha during normal years. Water used in supplemental irrigation had the highest marginal productivity and increase in rainfed production above 12% was achievable even under traditional practices. Under improved management, an average increase of 50% in total production can be achieved with a single supplemental irrigation. Water harvesting and supplemental irrigation are economically viable at the national level. Net benefits improved by about threefold for rice, fourfold for pulses and sixfold for oilseeds. Droughts have very mild impacts on productivity when farmers are equipped with supplemental irrigation.

1. Introduction

Rainfed agriculture is practiced on 80% of the world's agricultural land area, and generates about 70% of the world's staple foods, including most of the food in poor communities in developing and least-favoured areas (CA, 2007). The most recent estimates have put global rainfed croplands at 1.75 billion ha (Bha) at the end of the last millennium, or about 5.5 times the irrigated area in the world (GIAM, 2006). India ranks first among the countries that practice rainfed agriculture both in terms of extent (86 Mha) and value of production. Due to low land and labour productivity, poverty is concentrated in rainfed regions (Singh, 2001). While farmers in some high potential regions have increased yields by about 5% per annum in recent years, farmers in the semi-arid tropics of Asia (including India) have increased agricultural growth by less than 1%. Yield gap analyses for major rainfed crops find that farmers' yields are about one-half to one-quarter of achievable yields (CA, 2007). Grain yields vary from 1 to 2 tons t ha^{-1} in many rainfed areas, compared to attainable yields of more than 4 t ha^{-1} (Falkenmark et al., 2001). The large yield gap suggests there is much to gain by improving productivity in rainfed agriculture.

Rainfed agriculture in India is practiced under a variety of soil type, agro-climatic and rainfall conditions ranging from 400 mm to 1600 mm per annum. Rainfall is a random input and its variation and intensity are high in areas of low rainfall. Rockstrom and Falkenmark (2000) note that a decrease of one standard deviation from the mean annual rainfall often leads to a complete loss of the crop. Dry spells (or monsoonal breaks), which generally involve 2–4 weeks of no rainfall during critical crop growth stages, causing partial or complete crop failures, often occur every cropping season. Kanwar (1999) has identified adverse meteorological conditions resulting in long dry spells and droughts, unseasonal rains and extended moisture stress periods, with no mechanisms for storing or conserving the surplus rain to use during the scarcity/deficit periods, which comprise the major cause of low yields and heightened distress in rainfed regions.

Supplemental irrigation is a key strategy, so far underutilized on a regional basis, to unlock rainfed yield potentials. The existing

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evidence indicates that supplemental irrigation ranging from 50 to 200 mm/season (500–2000 m^3 ha^{-1}) is sufficient to mediate yield reducing dry spells in most years and in rainfed systems (Wani et al., 2003). Since irrigation water productivity is much higher when used conjunctively (supplemental) with rainwater, it is logical that, under limited water resources, priority in water allocation may be given to supplementary irrigation (Agarwal, 2000; Joshi et al., 2005). On a regional basis, collecting small amounts of runoff using limited macro-catchments during the rainy season, using this resource for supplementary irrigation and adopting improved agronomic practices can improve agricultural production in rainfed areas (Pathak et al., 2009). The Consultative Group on International Agricultural Research (CGIAR) Challenge Program on Water and Food supported a study of the available runoff in the dominant rainfed regions of India, with the goal of examining the hydrologic and economic potential for improving agricultural productivity. That study, as a part of the ‘Strategic Analysis of India’s National River Linking Project,’ had the following objectives:

(i) To identify the dominant rainfed districts for major rainfed crops in India.
(ii) To assess surplus runoff for water harvesting and supplemental irrigation and the irrigable area at the district level.
(iii) To estimate regional (district level) water use efficiency and the effect of supplemental irrigation on production of selected rainfed crops.
(iv) To conduct a preliminary economic analysis of water harvesting and supplemental irrigation in rainfed areas.

2. Methods of analysis

Districts are the primary administrative and planning units in India, and all data sets pertaining to agriculture, water resources, climate, human development and related parameters are available at the district level. There are 604 districts in India and the average size of a district is about 500,000 ha. We chose districts as the level of analysis for this research.

2.1. Identification of dominant rainfed districts for different crops

Kerr (1996) and the National Commission on Agriculture (1976) classify a district as a ‘rainfed district’ if the irrigated area in the district is less than 30%. Other studies use a variable proportion based on program objectives. The main limitation of these classifications is that they do not consider the distribution of crops in the district. An improved criterion for the identification of rainfed districts for a given crop is based on total rainfed area of the crop in the district (CRIDA, 1998). Such an approach helps identify the dominant districts contributing significantly in terms of rainfed area at the national level. We consider ‘dominant rainfed districts’ for a given crop to be those that cumulatively contain 85% of the rainfed production area within India. In our analysis we examine sunflower, soybean, rapeseed mustard, groundnut, castor, cotton, sorghum, pearl millet, maize and pigeon peas in *kharif* (rainy season) and linseed and chickpeas in *rabi* (winter season). We have prepared district-level, 5-year averages (1995–2000) of irrigated area, production and total cropped area.

2.2. Assessment of available surplus runoff for water harvesting and supplemental irrigation

In India, the normal southwest monsoon, which delivers about 70% of annual rainfall, extends from June to September. This is also the main season (*kharif*) for cultivation of rainfed crops. As total rainfall is spread over a few rainy days with fewer rain events (about 100 h per season) of high intensity, surface runoff can cause temporary water stagnation in agricultural fields. This surface runoff, or ‘green water,’ has a very low productivity. To assess water availability for harvesting during the rainy season, we have analyzed crop water balances for the season and for the whole year, for each of the selected crops in the identified districts. Utilizing available data on actual rainfall, normal rainfall and normal potential evapotranspiration (PET), we have adopted the following methodology:

(i) *FAO Water Balance Analysis* (FAO, 1977, 1998) for the cropping season for individual crops provided information on water surplus and deficits during the season. The start of the growing season (SGS) was considered when actual evapotranspiration (AET)/potential evapotranspiration (PET) of that week was >0.5 and consecutive 3 weeks had AET/PET >0.5 to ensure continuity in water availability to crops after the onset of the monsoon. The end of the growing season (EGS) was considered during the week AET/PET for the week was <0.25 and the consecutive 3 weeks had AET/PET less than 0.25. The length of the growing season (LGS) which represents the water availability period was calculated as, LGS = EGS-SGS + 1.
(ii) *Water Requirement Satisfaction Index* (WRSI, Verdin and Klaver, 2002) was used to assess the sufficiency of rainfall vis-à-vis the crop water requirements. Surplus in the water balance was taken mostly as runoff. The seasonal deficit index was calculated using: $1 - (\mathrm{AET}/\mathrm{PET})$.
(iii) *Thornthwaite Water Balance* (McCabe and Markstrom, 2007) was carried out for the annual climatic water balance analysis. This provided estimates for surplus and deficit periods during the year and helped in designing suitable management plans to augment water resources within the year.

2.3. Estimation of seasonal rain water use efficiency and production potential of rainfed crops

Water use efficiency (WUE) is normally defined as grain yield (or value of the produce) per unit of water used (kg/ha/mm, $/ha/mm, Molden, 2001). Regional rainwater use efficiency (RWUE) can be obtained by aggregating the field-scale rainwater use efficiency of individual fields. However, its estimation at regional (district) level is difficult as the data requirement is quite large (in terms of productivity values from each parcel of land, measurement of water inflow/outflow as surface or sub-surface flow, etc.). We use a simple method to estimate RWUE by utilizing existing productivity statistics and estimates of the rainfall utilized for crop production (i.e., rain water use efficiency as a ratio of productivity at district level to effective rainfall). RWUE, thus, derived would be lower than its estimated values, available at the farm level (as soil properties are aggregated) and would also result in a conservative estimate of production potentials based on these values. We aggregate RWUE at the district level for major rainfed crops. At the field level, the effective rainfall was estimated by the procedure developed under CROPWAT, and water use efficiency was estimated as the ratio of crop productivity at the district level (5-year average) to effective rainfall received at the district.

The estimated values may be lower in comparison to the experimental database from national experimental stations mainly due to variations in levels of inputs and adoption of improved rainfed technologies by farmers based on their socio-economic background, technology penetration and market conditions. Achievable yields from on-farm trials and long-term average rainfall for each dominant rainfed district and for different rainfed crops were used for estimating the “achievable” water use efficiency. Production projections were made for different crops in the respective rainfed districts using the information on regional rainwater use efficiency from both scenarios, namely; district productivity averages and on-farm trials hereafter referred as "traditional practices" and "improved technologies", respectively. We examined also the effect of supplemental irrigation of 100 mm at the reproductive stage under normal and drought conditions and we developed the following scenarios.

(i) Two application efficiencies representing traditional application (flood irrigation with 60% application efficiency) and improved water application technology, such as alternate furrow irrigation (with 70% application efficiency) were envisaged during normal rainfall years.
(ii) Application efficiencies of 65% and 75% were assumed for traditional and improved methods of water application during drought years. Experience shows that farmers achieve higher efficiency in water utilization during droughts.

2.4. Economics of water harvesting and supplemental irrigation

We define the annual net benefit from supplemental irrigation as the difference between the gross annual benefits from supplemental irrigation and the annualized cost of the capital investment in rainwater harvesting, adjusted appropriately for interest and depreciation. We assume that harvested rainwater is utilized for the existing crops and accordingly the returns are considered for existing crops only. However, our analysis provides insight regarding how farmers might diversify and move up the value chain for enhanced benefits, once an assured source of water supply is available (Bouma et al., 2005). We evaluate benefits using crop prices and the yield differences with supplemental irrigation. We took the Minimum Support Price for each crop (Agricultural Statistics of India, 2005–2006) as it is a unique and guaranteed remunerative price announced by the government at the commencement of the cropping season.

3. Results and discussion

3.1. Dominant rainfed districts for different crops in India

Rainfed areas in India are highly diverse, ranging from resource-rich areas with good agricultural potential to resource-constrained areas with limited potential. At present, an estimated 60% of the 142.2 Mha net cultivated area is rainfed, which contributes to 44% of total food grain production. Rosegrant et al. (2002) have estimated that even by 2025, one-third of India's cereal production will be contributed by rainfed areas. Most of India's (coarse) cereals (91%), pulses (91%), oilseeds (80%) and cotton (65%) are produced in rainfed areas. Small areas of almost all rainfed crops are scattered in most of the districts, except for a few crops such as soybeans and linseed that have specific agro-climatic requirements. We have identified crop-specific 'dominant rainfed districts' that describe the region in which 85% of each rainfed crop is produced (Table 1).

Each of the rainfed crops has an agro-climatic niche and its cultivation is concentrated in a subset of the total districts. Productivity and other development activities related to the specific crop should be taken up first in these districts to ensure a major impact on productivity.

3.2. Assessment of available surplus runoff for water harvesting and supplemental irrigation

Local harvesting of a small part of the surplus rainfall and utilizing the same for supplemental/protective irrigation to mitigate the impacts of devastating dry spells offer a good opportunity in the fragile rainfed regions (Rockstrom, 2001, 2003; Sharma et al., 2005; Wani et al., 2003). For national-/regional-level planning on supplementary irrigation, an assessment of the total and available surplus runoff and the potential for its gainful utilization is required. We estimate the total surplus in each district using the seasonal and annual crop water balance model (Section 2.2). Regional surplus is obtained by adding the surplus from individual dominant districts identified for each crop. We estimate that 115 Bm^3 of runoff are generated on 39 Mha of rainfed area. The spatial distribution of runoff by agroecological sub regions and river basins is shown in Fig. 1.

Based on experiences from watershed management research and large-scale development efforts, practical harvesting of runoff is possible only when the harvestable amount is more than 50 mm or greater than 10% of the seasonal rainfall (minimum utilizable

Table 1
Total and 'dominant districts' cultivating important rainfed crops in India.

Rainfed crops	Total number of districts cultivating rainfed crop	Dominant districts cultivating rainfed crop[a]
Sunflower	224	11
Soybeans	202	21
Rapeseed mustard	265	29
Groundnut	316	50
Castor	202	12
Cotton	296	30
Sorghum	346	71
Pearl millet	346	43
Maize	346	67
Pigeon pea	266	83
Chickpea	346	85

[a] Number of districts covering cumulative 85% of rain-fed area for the specific crop.

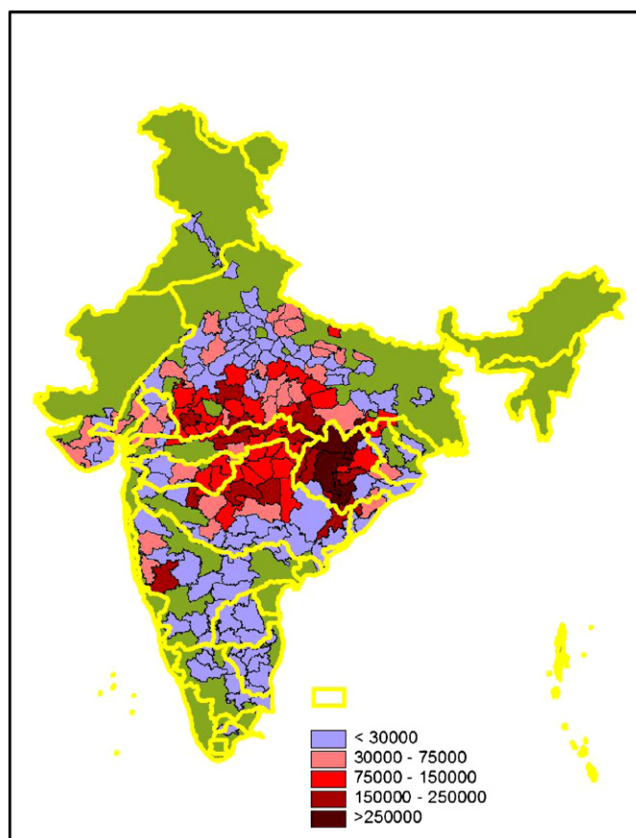

Fig. 1. Spatial distribution of surplus runoff (ha-m) across dominant rainfed districts and river basins of India.

Table 2
Potentially harvestable surplus runoff available for supplemental irrigation from different rainfed crops under the dominant rainfed districts of India.

Crop/crop group	Rainfed crop area (M ha)	Surplus runoff (BM^3)
Rice	6.329	41.218
Finger millet	0.303	1.538
Maize	2.443	7.719
Pearl millet	1.818	3.599
Sorghum	2.938	7.717
Total (coarse cereals)	*7.502*	*20.574*
Cotton	3.177	7.575
Castor	0.028	0.145
Groundnut	1.663	3.426
Linseed	0.590	3.063
Sesame	1.052	4.166
Soybeans	2.843	13.292
Sunflower	0.098	0.118
Total (oilseeds)	*6.273*	*24.212*
Chickpea	3.006	13.047
Green gram	0.458	0.801
Pigeon pea	1.823	6.593
Total (pulses)	*5.288*	*20.441*
Grand total	28.568	114.022

Table 3
Irrigable area through supplemental irrigation (100 mm per irrigation) during normal monsoon and drought years under different rainfed crops.

Crop/crop group	Rainfed crop area (M ha)	Irrigable area (M ha)	
		During normal monsoon	During drought season
Rice	6.329	6.329	6.215
Finger millet	0.303	0.266	0.224
Maize	2.443	2.251	1.684
Pearl millet	1.818	1.370	0.837
Sorghum	2.938	2.628	1.856
Total (coarse cereals)	*7.502*	*6.515*	*4.601*
Cotton	3.177	2.656	1.725
Castor	0.028	0.025	0.022
Groundnut	1.663	1.096	0.710
Sesame	1.052	0.919	0.741
Soybeans	2.843	2.843	2.667
Sunflower	0.098	0.059	0.030
Total (oilseeds)	*5.684*	*4.942*	*4.170*
Chickpea	3.006	2.925	2.560
Pigeon pea	1.823	1.710	1.374
Total (pulses)	*4.829*	*4.635*	*3.934*
Grand total	27.521	25.077	20.645

runoff (CRIDA, 2001). Therefore surplus runoff generating areas/districts were identified after deleting the districts with seasonal surplus of less than or equal to 50 mm of surplus (10.25 Mha) and those districts generating runoff of less than 10% of seasonal rainfall (0.25 Mha).

The total estimated runoff surplus for various rainfed crops is about 114 Bm^3 (from about 28.5 Mha) which could be considered for water harvesting (Table 2). Among individual crops, rainfed rice contributes a higher surplus (41.2 Bm^3 from an area of 6.33 Mha) followed by soybeans (13.0 Bm^3 from 2.8 Mha). A small deficit of rainfall for meeting crop water requirement was noticed for crops including groundnut, cotton, chickpea and pigeon pea.

Long- and short-term agricultural droughts and more pronounced meteorological droughts occur often in the rainfed areas served by monsoons. A year is declared as a 'drought year' when annual rainfall is less than 20% of long-term normal rainfall (Swami, 2002). Though there is a good amount of surplus available as runoff in a season, all the runoff is not available at one time. For the main southwest Indian monsoon, usually there are two peaks of rainfall, the first occurring immediately after the onset of the monsoon and the second during its withdrawal phase. During these two periods, there is a likely certainty in overflows (Ramakrishna et al., 1998) with higher prospects during the withdrawal phase. Thus, at least some runoff during the withdrawal time in September is likely even if the early period is affected by aberrations in the monsoon. This would result in a harvestable surplus, which could be used subsequently during the flowering or grain-filling stages of rainfed crops.

Normally, farmers (depending on the method of irrigation) apply an irrigation depth of 20–50 mm as supplemental/deficit irrigation in rainfed areas. In canal command areas, about 60–75 mm of water are applied per irrigation. The objective of supplemental irrigation is to adequately recharge the upper dry soil profile and connect it with the moist profile prevailing in the deeper soil layers, to provide continuity to the flow process. We considered irrigations of 100 mm including conveyance and other losses. This 100 mm depth might seem large, but it reflects the large number of untrained water managers, uneven farm lands and the lack of suitable irrigation infrastructure available with rainfed farmers.

We have estimated the irrigable area for a single supplemental irrigation of 100 mm at the reproductive stage of the crop during normal rainfall and drought years (Table 3). Runoff during drought years is assumed to be 50% of runoff surplus during normal rainfall years (based on authors' estimates for selected districts and rainfed crops in Andhra Pradesh, India). Of the 114 Bm^3 available as surplus about 28 Bm^3 (19.4%) of water are needed for providing supplemental irrigation to an area of 25 Mha during normal monsoonal year thus leaving about 86 Bm^3 (80.6%) to meet river/environmental flow and other requirements. During drought years also about 31 Bm^3 are still available after providing one supplemental irrigation for 20.6 Mha. Thus water harvesting and supplemental irrigation in the dominant rainfed districts might not cause significant downstream impacts in normal and or drought years (Amarasinghe et al., 2009).

3.3. Seasonal rainwater use efficiency and production potential of rainfed crops

The average water use efficiency values and their ranges are given under Table 4. The estimated values may be lower in comparison to levels achieved on experimental stations due to variations in levels of inputs and adoption of improved rainfed farming technologies by farmers. Achievable yields from on-farm trials and long-term average rainfall for each dominant rainfed district and for different rainfed crops were used to estimate the "achievable" water use efficiency (Table 5). The maximum and minimum values represent the spatial variability among dominant districts. The improved technologies involve adoption of improved varieties, application of recommended doses of fertilizers, better management and follow-up on recommended packages of practices. A comparison of data in Tables 4 and 5 reveals that in rice, pulses, coarse cereals, oilseeds (except groundnut) and sunflower and cotton, there is a scope for improvement of water use efficiency by two to four times. The improvements can be attributed to availability of superior management practices including improved varieties/hybrids.

Table 4
Estimated rainwater use efficiency (kg/ha/mm) for different crops under traditional practices[a] for the dominant rainfed crop districts of India.

Crop	Average	Maximum	Minimum
Rice	3.30	7.09	1.19
Finger millet	2.76	7.76	1.27
Maize	2.34	5.51	1.36
Pear millet	2.37	3.90	0.61
Sorghum	1.37	2.79	0.53
Cotton	0.38	1.52	0.17
Castor	0.72	1.04	0.33
Groundnut	2.57	4.14	1.33
Sesame	0.96	1.68	0.33
Soybeans	1.74	2.53	1.29
Sunflower	1.71	2.21	1.20
Chick pea	1.74	3.28	0.81
Pigeon pea	1.67	3.41	0.20

[a] Based on district-level data base.

3.3.1. Rainfed production improvement through supplemental irrigation

Previous analysis has shown there is a large opportunity in terms of potential gains in rainfed crop yields and that hydro-climatic deficiency determines the boundary conditions of potential yields (Sharma, 2009). Production projections were made for different crops in the respective rainfed districts using information on regional rainwater use efficiency from both scenarios, namely; "traditional practices" and "improved technologies" and supplemental irrigation of 100 mm at the reproductive stage. The estimated production projections for each crop and crop group under traditional practices and over two types of seasons (normal and drought) are given in Table 6. Additional production was a product of irrigable area (Table 3), water use efficiency (Table 4) and the amount of irrigation. The irrigable area through supplemental irrigation for different crops during the drought season varies between 50% for sunflower to 98% for rice of the irrigable area during the normal season.

With the continuation of age-old management practices (traditional), an average of 12% increase in production cutting across drought and normal seasons is realizable only with supplemental irrigation (Table 6). Low current agricultural yields in rainfed agriculture, which are often blamed on rainfall deficits, are in fact often caused by other factors. Improved technologies, along with water, are important in harnessing the potential benefits. Under improved management practices an average increase of 50% in total production cutting across drought and normal seasons is realizable with supplemental irrigation from the rainfed area of 27.5 Mha (Table 7). Production enhancement in the drought season in case of rice crop is high due to higher water application efficiency and the sufficient surplus to bring almost the entire rice cultivated area under supplemental irrigation. This would also indicate that large tracts of rainfed rice cultivated area are covered under high rainfall zones with sufficient surplus for rainwater harvesting. A similar situation could be observed for soybeans, which also reflects the concentration of crop-growing area in high rainfall zones. In case of other crops, though water

Table 5
Estimated water use efficiency values based on 'achievable yields' (improved technologies) for different rainfed crops[a] of India.

Crop	Water use efficiency (kg/ha/mm)		
	Average	Maximum	Minimum
Rice	9.40	11.29	7.34
Finger millet	6.80	8.01	6.30
Maize	10.97	13.70	8.44
Pear millet	8.67	11.31	6.96
Sorghum	13.51	17.72	11.22
Cotton	1.60	1.97	1.23
Castor	3.50	3.67	3.18
Groundnut	3.75	4.69	2.88
Sesame	3.11	3.68	2.48
Soybean	7.11	8.15	5.38
Sunflower	3.05	3.13	2.97
Chick pea	5.19	6.25	3.90
Pigeon pea	2.44	2.96	1.86

[a] Based on long-term on-farm data from the national network on rainfed agriculture.

Table 6
Production projections of rainfed crops with variable supplemental irrigation efficiency (SIE) during normal monsoon and drought seasons in India.

Crop/crop group	Traditional production ('000 ton)	Additional production ('000 ton)			
		Normal monsoon with SIE		Drought season with SIE	
		60%	70%	65%	75%
Rice	7,612	1,204	1,405	1,275	1,471
Finger millet	271	44	51	38	44
Maize	2,996	347	405	282	325
Pearl millet	1,902	192	224	126	145
Sorghum	3,131	273	318	204	236
Total (coarse cereals)	*8,300*	*856*	*998*	*650*	*750*
Cotton	430	50	59	36	42
Castor	10	1	1	1	1
Groundnut	1,182	157	183	113	131
Sesame	365	75	87	63	72
Soybeans	2,607	283	330	285	329
Sunflower	49	5	6	3	3
Total (oilseeds)	*4,213*	*521*	*607*	*465*	*536*
Chickpea	2,367	301	352	287	331
Pigeon pea	1,350	163	190	148	171
Total (pulses)	*3,717*	*464*	*542*	*435*	*502*
Grand total	24,272	3,095	3,611	2,861	3,301

Table 7
Production projection of rainfed crops with variable supplemental irrigation efficiency (SIE) and improved technology during normal monsoon and drought seasons in India.

Crop/crop group	Traditional production (M tons)	Additional production (M ton)			
		Normal monsoon, with SIE		Drought season, with SIE	
		60%	70%	65%	75%
Rice	7.612	3.549	4.141	3.776	4.357
Finger millet	0.271	0.107	0.124	0.097	0.112
Maize	2.996	1.495	1.744	1.221	1.408
Pearl millet	1.902	0.717	0.836	0.481	0.555
Sorghum	3.131	2.091	2.439	1.616	1.864
Total (coarse cereals)	*8.300*	*4.410*	*5.143*	*3.415*	*3.939*
Cotton	0.430	0.252	0.294	0.178	0.206
Castor	0.010	0.005	0.006	0.005	0.006
Groundnut	1.182	0.244	0.284	0.176	0.203
Sesame	0.365	0.173	0.202	0.153	0.176
Soybeans	2.607	1.225	1.429	1.250	1.443
Sunflower	0.049	0.011	0.012	0.006	0.007
Total (oilseeds)	*4.213*	*1.658*	*1.933*	*1.590*	*1.835*
Chickpea	2.367	0.910	1.061	0.866	1.000
Pigeon pea	1.350	0.242	0.282	0.21	0.245
Total (pulses)	*3.717*	*1.152*	*1.344*	*1.078*	*1.245*
Grand total	24.272	11.021	12.856	10.037	11.582

application efficiency is higher during drought scenario, the lack of surplus to cover the entire area reduces total production. Significant production improvements can be realized in rice, sorghum, maize, cotton, sesame, soybeans and chickpea. Trials of water harvesting and its strategic application (supplementary irrigation) in Burkina Faso, Kenya, Niger, Sudan and Tanzania have also shown increased yields of two to three times those achieved in dryland farming (FAO, 2002). Secured crop water supply (though of a limited amount) during critical drought spells reduces the risks of crop failure thereby increasing farmers' incentives to invest in farm inputs, such as fertilizers, improved seeds, crop protection and diversification (Falkenmark et al., 2001).

3.4. Economics of water harvesting and supplemental irrigation

While it appears that supplemental irrigation offers scope for enhancing production from rainfed crops across different agro-ecologies/districts, economic viability is essential to support farm-level adoption. The available literature has good evidence on the technical and financial viability of water harvesting structures for improvement of productivity and diversification of agriculture in rainfed areas (Oweis, 1997). The cost of providing supplemental irrigation varies between states, regions and locations (Sharda, 2003). Farmers mainly use refurbished natural depressions or dug-out ponds and check-dams for harvesting and storing surplus runoff. Depending upon soil conditions these structures may be lined with different materials and have variable cost of construction (Samra, 2007; *personal communication*; Table 8).

We made a simple analysis based on the national average cost of lined dug-out ponds and check-dams (INR 18,500/ha) normally used as rainwater harvesting structures for providing supplemental irrigation to rainfed crops. The crop-wise annualised cost, considering useful life of lined structures as 20 years, is given in Table 9. An estimated INR 50.91 billion (~ US$ 1 billion) is annually required to provide supplemental irrigation to 27.5 Mha of rainfed cultivated land and about half of that amount is required for the production of rice and coarse cereals only. The benefit is evaluated based on the price of the crop and the yield difference from supplemental irrigation. Gross benefits are comparable to the annualized costs even under traditional (business-as-usual scenario) practices and are much higher when farmers adopt the standard improved practices. The data suggest that even though pulses account for 17% of the total annualized cost, supplemental irrigation can generate more than 40% of total gross benefits under all scenarios, suggesting that supplemental irrigation is highly beneficial for pulse crops.

Table 10 shows crop-wise net benefits of supplemental irrigation. Provision of only supplemental irrigation (non-adoption of improved practices) generates good net benefits for only pulses and oilseed crops, indicating that supplemental irrigation is highly beneficial for high-value but less stress-resistant crops. Low-value coarse cereals seem to be less responsive to supplemental irrigation alone. With the adoption of improved practices, in conjunction with supplemental irrigation, net benefits become positive for all crops except pearl millet, indicating the need for development/general adoption of high-yielding varieties of pearl millet, which are responsive to irrigation and improved practices. Pearl millet, sorghum and maize have very low harvest indices. However, net benefits improve by about, three times for rice, four times for pulses and six times for oilseeds. Droughts appear to have a very mild impact when farmers are equipped with supplemental irrigation and the net benefits remain stable even when runoff during a drought is reduced by 50%.

Table 8
Cost of different water harvesting structures[a] (Indian Rs.[b]) per hectare of the service area at different locations in India.

Location/state	Minimum	Maximum	Average
Bagbahrar (Chhatisgarh)	4,100	29,200	11,000
Dindori (Madhya Pradesh)	6,800	25,000	18,000
Keonjhar (Orissa)	19,400	35,000	27,000
Darisai (Jharkhand)	8,300	27,800	18,000
National average			18,500

National Rainfed Area Authority of India, New Delhi.
[a] Lined dug-out ponds and check dams.
[b] 1 USD ~Indian Rs. 50.

Table 9
Crop wise annualized cost and gross benefits from variable supplemental irrigation efficiency (SIE) under traditional practices and with improved technologies during normal monsoon and drought conditions.

Crop/crop group	Rainfed crop area (M ha)	Annual cost (billion rupees)	Gross benefits under traditional practices (billion Rs.) with		Gross benefits under improved technologies (billion Rs.) with	
			60% SIE during normal monsoon	65% SIE during drought	65% SIE during normal monsoon	75% SIE during drought
Rice	6.329	11.71	6.86	7.27	20.23	21.52
Finger millet	0.303	0.56	0.91	0.82	2.23	2.02
Maize	2.443	4.52	1.64	1.33	7.05	5.75
Pearl millet	1.818	3.36	0.50	0.33	1.88	1.26
Sorghum	2.938	5.44	0.83	0.62	6.38	4.94
Total (coarse cereals)	*7.502*	*13.88*	*3.88*	*3.10*	*17.54*	*13.96*
Cotton	3.177	5.88	2.83	2.02	14.15	10.00
Castor	0.028	0.05	0.05	0.05	0.22	0.21
Groundnut	1.663	3.08	5.70	4.12	8.86	6.40
Sesame	1.052	1.95	2.95	2.48	6.82	6.03
Soybeans	2.843	5.26	4.32	4.35	18.69	19.09
Sunflower	0.098	0.18	0.18	0.11	0.36	0.20
Total (oilseeds)	*5.684*	*10.52*	*13.20*	*11.11*	*34.95*	*31.93*
Chick pea	3.006	5.56	16.25	15.48	49.05	46.70
Pigeon pea	1.823	3.37	6.34	5.74	9.39	8.23
Total (pulses)	*4.829*	*8.93*	*22.59*	*21.22*	*58.44*	*54.93*
Grand total	27.520	50.91	49.36	44.71	145.31	132.34

Table 10
Crop wise net benefits from variable supplemental irrigation efficiency under traditional practices and improved technologies during normal monsoon and drought conditions.

Crop/crop group	Rainfed crop area (M ha)	Annual cost (billion Rs.)	Net benefits under traditional practices (billion Rs.) with		Net benefits under improved technologies (billion Rs.) with	
			60% SIE during normal monsoon	65% SIE during drought	65% SIE during normal monsoon	75% SIE during drought
Rice	6.329	11.71	−4.85	−4.44	8.52	9.81
Finger millet	0.303	0.56	0.35	0.26	1.67	1 46
Maize	2.443	4.52	−2.88	−3.19	2.53	1.23
Pearl millet	1.818	3.36	−2.86	−3.03	−1.49	−2.10
Sorghum	2.938	5.44	−4.60	−4.81	0.95	−0.50
Total (coarse cereals)	*7.502*	*13.88*	*−10.00*	*−10.78*	*3.66*	*0.08*
Cotton	3.177	5.88	−3.04	−3.85	8.27	4.12
Castor	0.028	0.05	0.00	0.00	0.17	0.16
Groundnut	1.663	3.08	2.62	1.04	5.79	3.32
Sesame	1.052	1.95	1.00	0.53	4.87	4.08
Soybeans	2.843	5.26	−0.94	−0.91	13.43	13.83
Sunflower	0.098	0.18	0.00	−0.08	0.18	0.01
Total (oilseeds)	*5.684*	*10.52*	*2.68*	*0.58*	*24.44*	*21.40*
Chickpea	3.006	5.56	10.69	9.91	43.49	41.14
Pigeon pea	1.823	3.37	2.96	2.37	6.02	4.86
Total (pulses)	4.829	*8.93*	*13.65*	*12.28*	*49.51*	*46.00*
Grand total	27.520	50.91	−1.56	−6.21	94.40	81.42

4. Conclusions

Rainfed lands have substantial unexploited potential for growth, yet the risks of crop failures, low yields and the insecurity of livelihoods are high due to the random behaviour of the monsoonal rainfall. Rainfed agriculture is mainly and negatively influenced by intermittent dry spells during the cropping season and especially at critical growth stages. A district-level analysis of rainfed crops in India shows that total water availability may not be the major problem in rainfed areas. For each crop there are a few dominant districts which contribute most to the total rainfed crop production. A feasible strategy for realizing the potential of rainfed agriculture in India (and elsewhere) appears to be harvesting a small portion of the available surplus runoff and using it for supplemental irrigation at critical crop growth stages. We have identified about 27.5 Mha of potential rainfed area, which not only accounts for most of the rainfed production but also generates sufficient runoff (114 Bm^3) for water harvesting. Rainfed production might be increased by 50% over this area by applying a single supplementary irrigation and with some improvements in agricultural practices. Rainwater harvesting and its use as supplementary irrigation are economically viable, even at the regional scale, and is more attractive for pulses and oilseed crops. Rainwater harvesting and supplemental irrigation might become important components of new development schemes in selected rural districts of India.

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